Airborne Radio Occultation (ARO) data assimilation achievements and future advances

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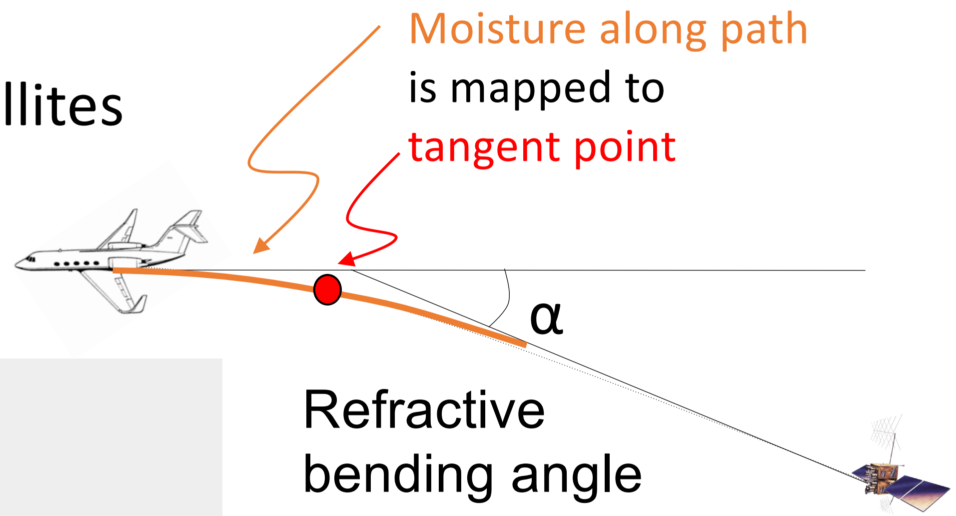
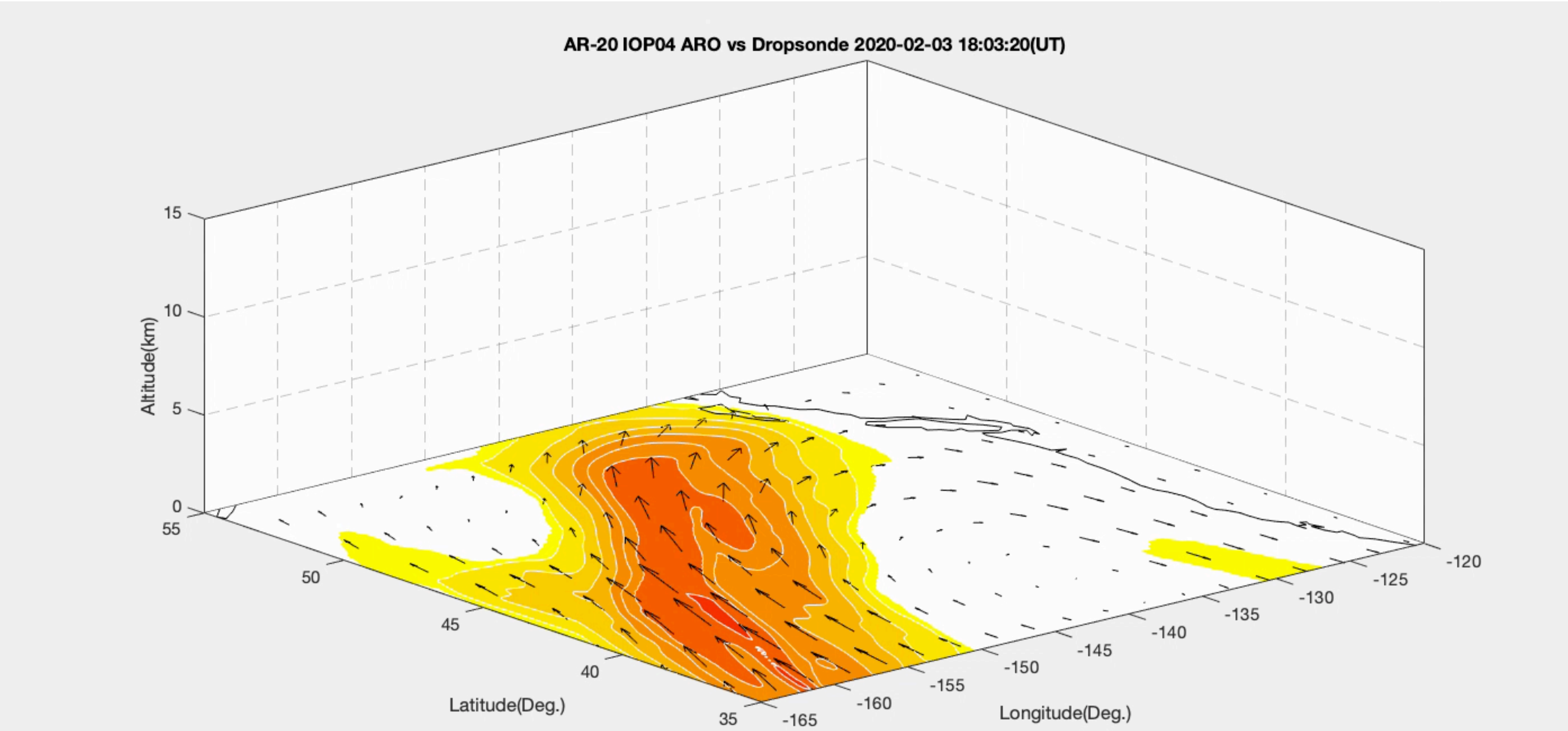
Airborne GNSS Radio Occultation

- Side-looking GNSS receiver tracks setting and rising satellites
- Nearly horizontal raypaths experience refractive delay





Contours are integrated vapor transport and vectors are direction of transport.

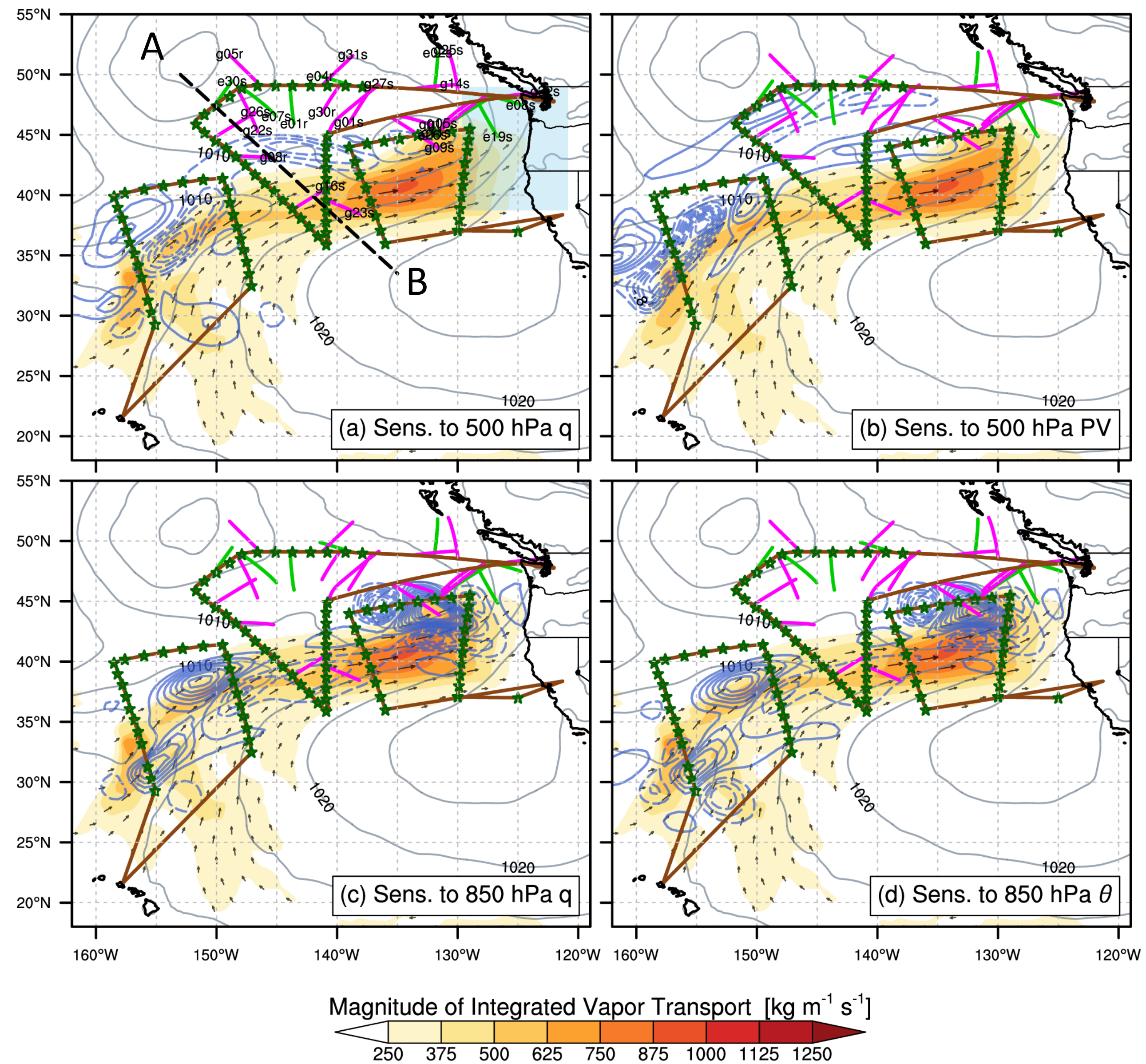
- Atmospheric humidity is a function of refractive delay

$$N = (n-1)\cdot 10^6 = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

Haase et al., 2014, GRL.

Targeting of dropsonde and ARO observations

- Aircraft targets
  - steep gradients in the AR water vapor
  - upper-level dynamics
  - model forecast sensitivity
- Sensitivity of the 12 hour accumulated precipitation in the PacNW to errors in
  - 500 hPa specific humidity
  - 500 hPa potential vorticity
  - 850 hPa specific humidity
  - 850 hPa potential temperature
- ARO samples off the flight track (A-B)
- We use some common sampling locations to establish the reliability of the data

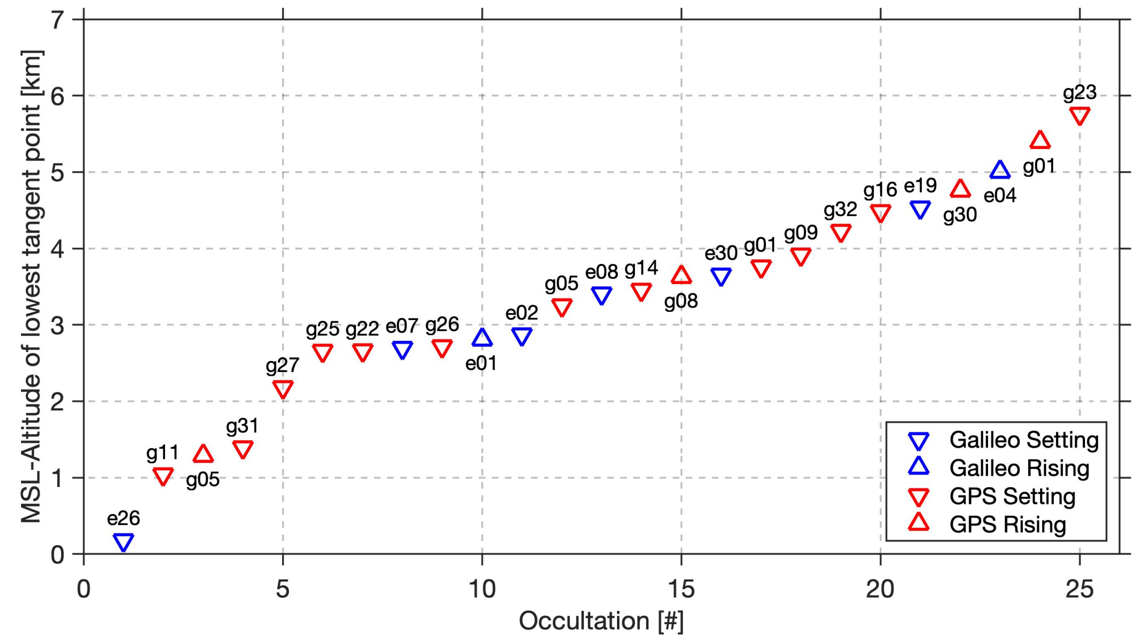


Multi-GNSS Airborne Radio Occultation Observations as a Complement to Dropsondes in Atmospheric River Reconnaissance, J. S. Haase, M.J. Murphy, B. Cao, F.M. Ralph, M. Zheng, L. Delle Monache, *J. Geophys. Res.*, submitted, 2021.

Significant increase in sampling the AR environment

- First radio occultation profiles (from space or aircraft) from Galileo
- First airborne rising satellite occultations
- 25 profiles in one 8 hour flight
- Vertical extent of profiles is flight level to below 5 km
- (Haase et al, 2014, Murphy et al., 2015 showed previously 4 per flight, all above 7 km.)

- 2018 IOP04 GPS + Galileo



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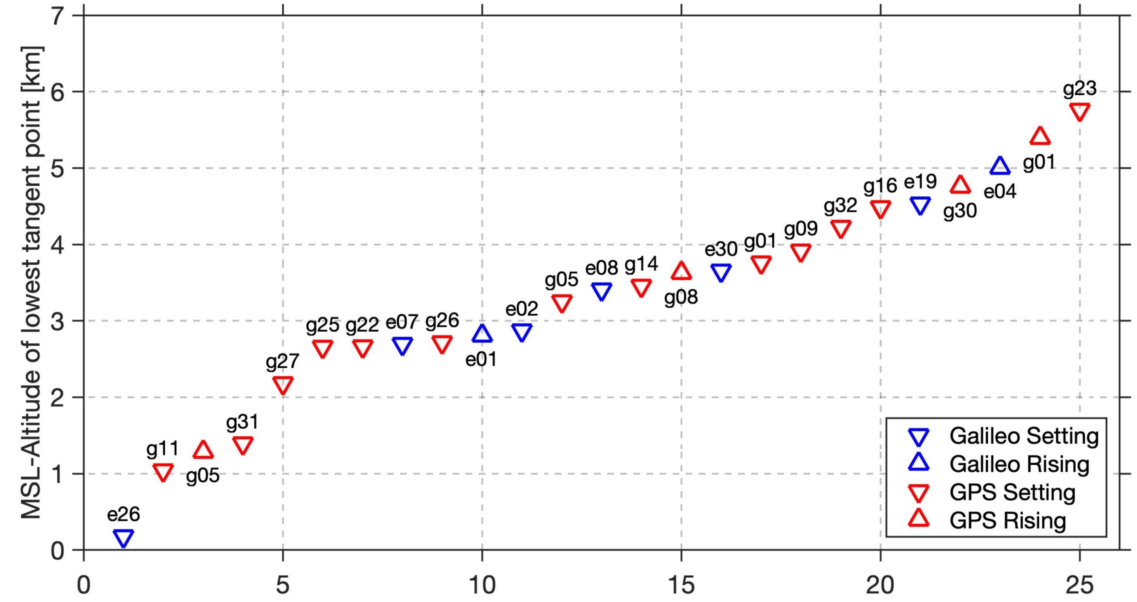
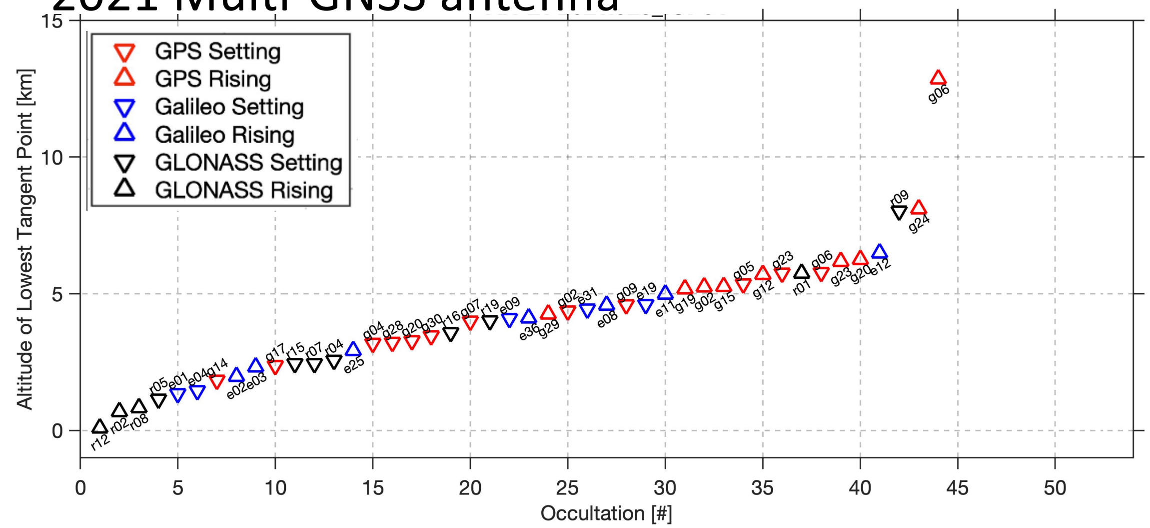
- Vertical extent of profiles is flight level to below 5 km
- (Haase et al, 2014, Murphy et al., 2015 showed previously 4 per flight, all above 7 km.)
- AR Recon 2021 Multi GNSS antenna producing ~45 profiles per flight, median height 3.6 km, GPS, Galileo, and GLONASS

- 2018 IOP04 GPS + Galileo

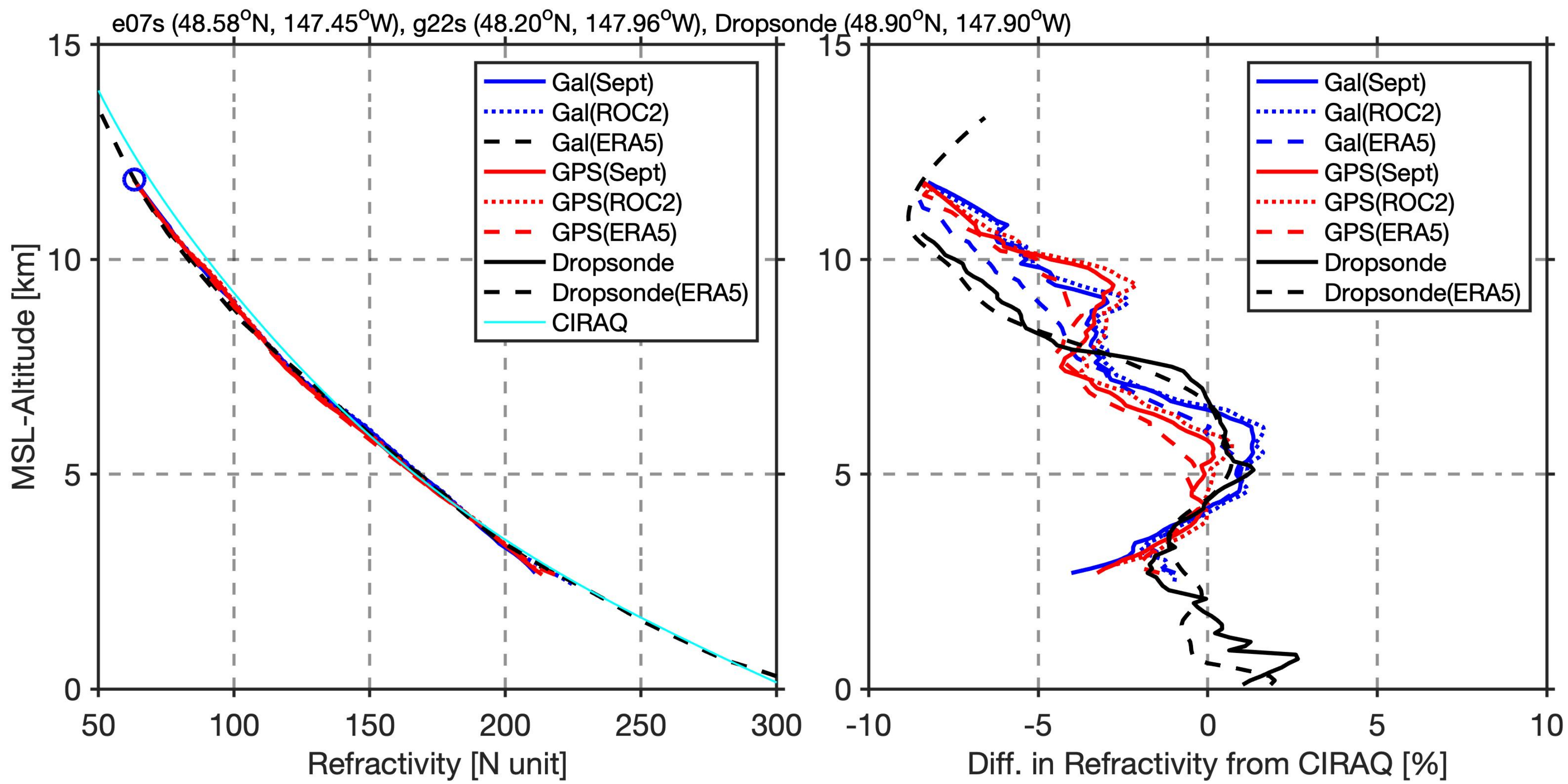


- 2021 Multi-GNSS antenna



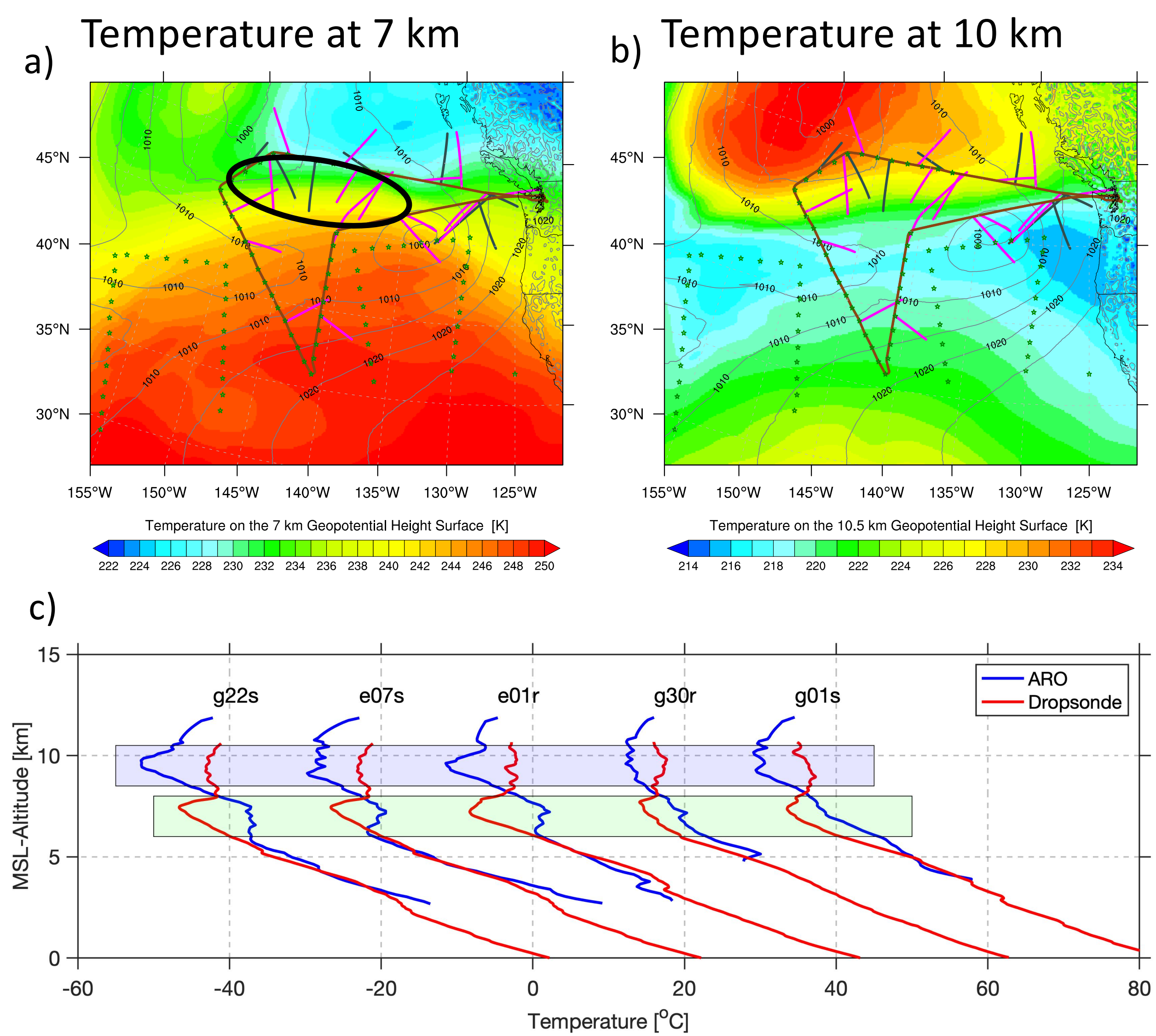
Data quality

- Two receivers, same occultation (dotted vs solid lines) show repeatability is better than 1%.
- Two closely spaced ARO profiles from GPS and Galileo – agree within 2%.
- ERA5 is close but does not capture high resolution vertical structure.
- Dropsondes differ by more than accuracy.



Exploiting the spatial coverage of ARO

- Temperature fields from WestWRF model experiment that assimilated dropsondes
- ARO profiles show cooler temperatures at 10km
- Dropsondes show cooler temperatures at 7 km
- Dropsonde + ARO are sensitive to variations in the tropopause height => tropopause folds.



ARO data assimilation experiments

Phase	26 Jan 0:00	**Atmospheric River offshore**
Phase	27 Jan 21:00	**Landfall**
Phase	29 Jan 0:00	**NonAR cyclogenesis**
Phase	27 Jan 3:00	**Landfall Oregon**
Phase	28 Jan 15:00	**Landfall and heavy precipitation Vancouver Is.**

Experiments (no cycling)

26 Jan								27 Jan								28 Jan								29 Jan								30 Jan				
0:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00	0:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00	0:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00	0:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00	0:00	3:00	6:00	9:00	12:00
						B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C		B/C

Experiments	26 Jan 18:00	Start Cold Run
Experiments	26 Jan 18:00	GEFS ensemble as IC/BC run forward for 4 days
Experiments	27 Jan 0:00	3DVar data assimilation 1 cycle on outer domain D01
Experiments	27 Jan 0:00	Free forecast for 4 days using updated analysis and B/C on nested grid with two domains D01 and D02
Observations		
G-4 Flights	26 Jan 18:00	RF01 2000 - 0200 Z
	26 Jan 18:00	ARO Observations available for DA = 25 profiles
C-130 HI	26 Jan 18:00	RF01 2000 - 0300 Z
C-130 HI	28 Jan 18:00	RF02 2000 - 0300 Z
C-130 CA	26 Jan 18:00	RF01 1900 - 0200 Z
C-130 CA	28 Jan 18:00	RF02 1900 - 0200 Z
	26 Jan 18:00 / 21:00 / 27 Jan 0:00	8 49 30 = 87 dropsondes total for DA
	28 Jan 18:00 / 21:00 / 29 Jan 0:00	8 25 18 = 51 dropsondes available for verification

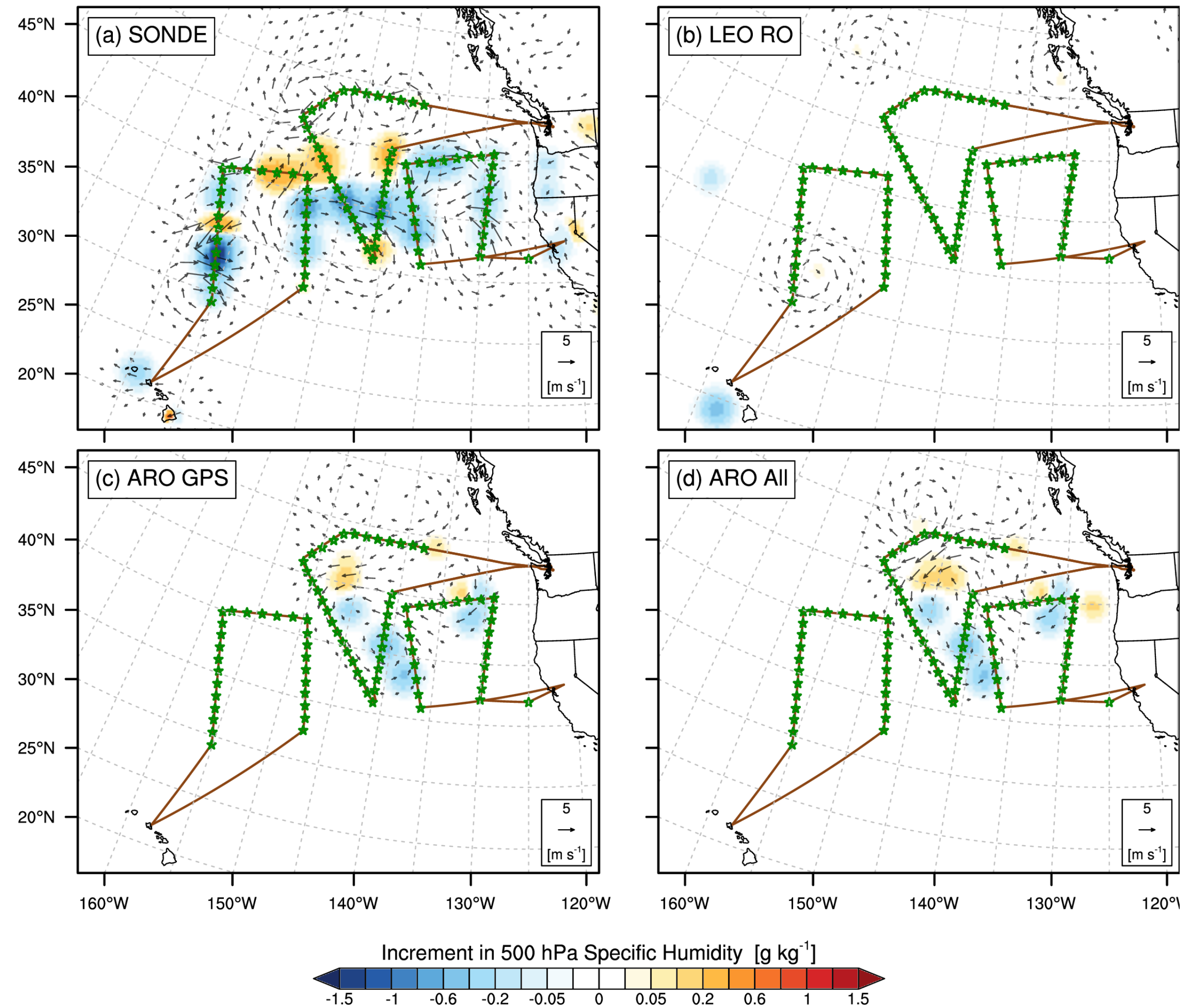
Config 07.01 (GEFS forcing with Ensembles)

	14.7X	
Description	two domains	
Forecast model	WRF-ARW V4.1	
DA System	WRFDA V4.1	
DA technique	3DVAR **No Cycling ASCII prepbufr**	
Initial/Bdry Conditi	GEFS Operational Forecast (from HAS 1.0 deg)	
# of ensembles	0 i.e. just the cntrl member (ens00)	
Domains	D01	D02
Assmilation	yes	no
Resolution	27 km	9 km
Mesh size	355 x 300	799 x 661
Nest feedbak	two way	two way
Model levels	48	
Model top	10 hPa	

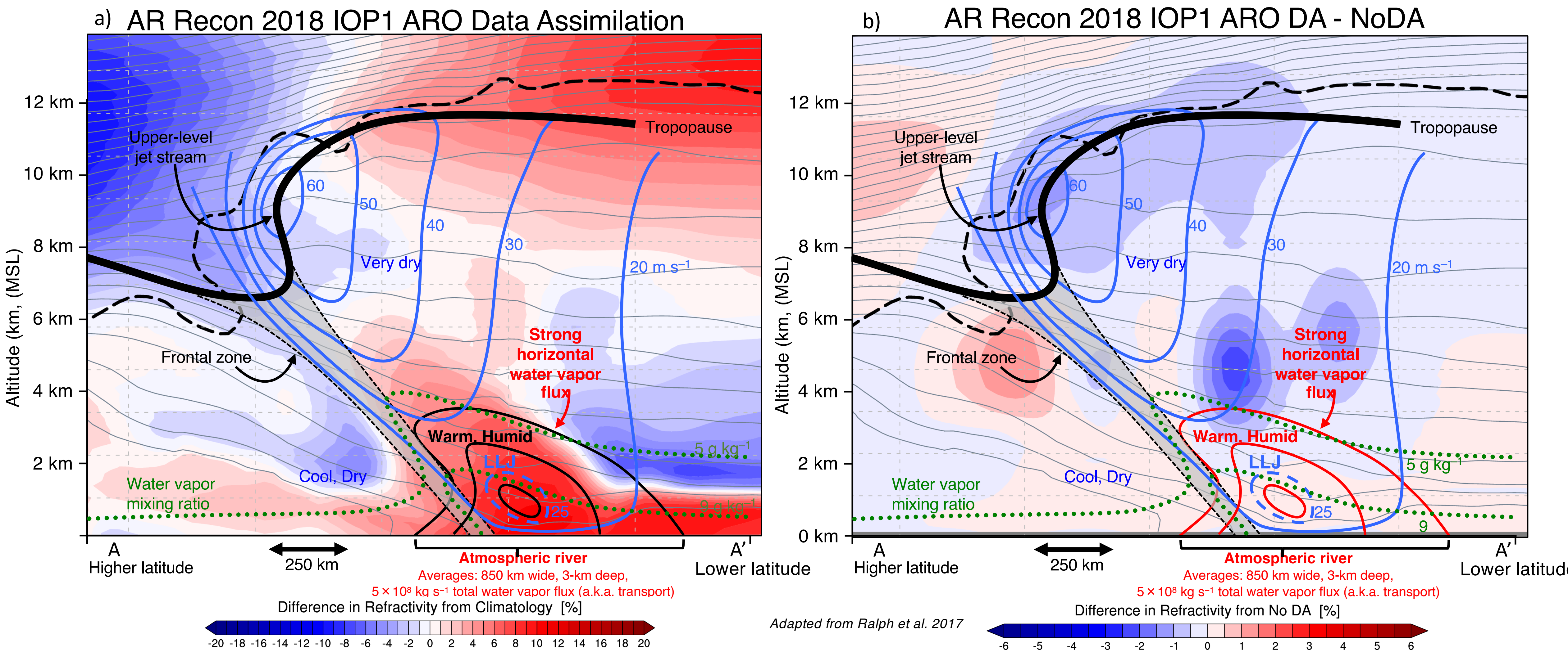
Microphysics	Thompson (Double-Moment)	
Cumulus	Grell-Freitas	Grell-Freitas
PBL	YSU scheme	
Land Surface	Unified Noah land-surface model	
Longwave	RRTMG	
Shortwave	RRTMG	
Background Error	NMC method (24-12 hr fcsts)	
	15 Jan - 15 Feb 2018	
	intitalized at 00 & 12 UTC	
BE System	WRFDA GENBE V1.0	
	BE Covariance 5	

ARO impact on initial conditions

- Impact on mid-level specific humidity
  - LEO RO – very few profiles in the domain, this is changing with new mission availability
  - ARO GPS provides impact in the interior of the flight path.
  - ARO GPS+Galileo reinforces that moisture increase
- The impact of the ARO data produces adjustments of the model first guess in the correct directions as cross validated by the dropsonde impact and usefully extends that impact into otherwise unobserved areas.



Refractivity anomaly highlights AR structure



Airborne Radio Occultation on the NOAA G-IV

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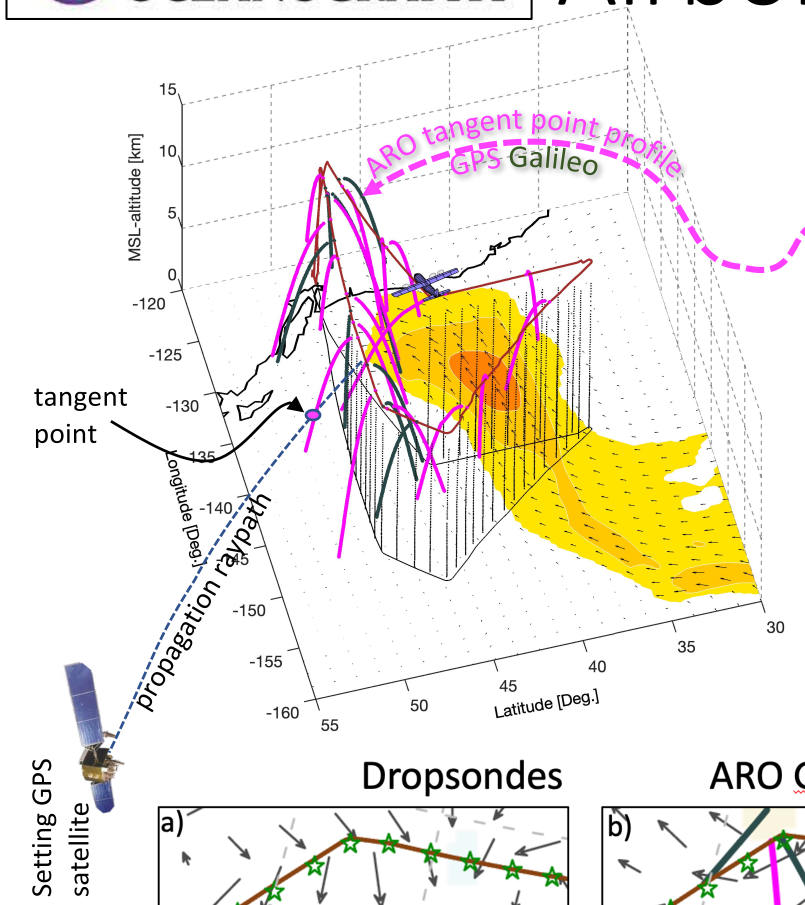
Results from AR Recon 2018

Haase et al., JGR – Atmospheres, 2021, submitted

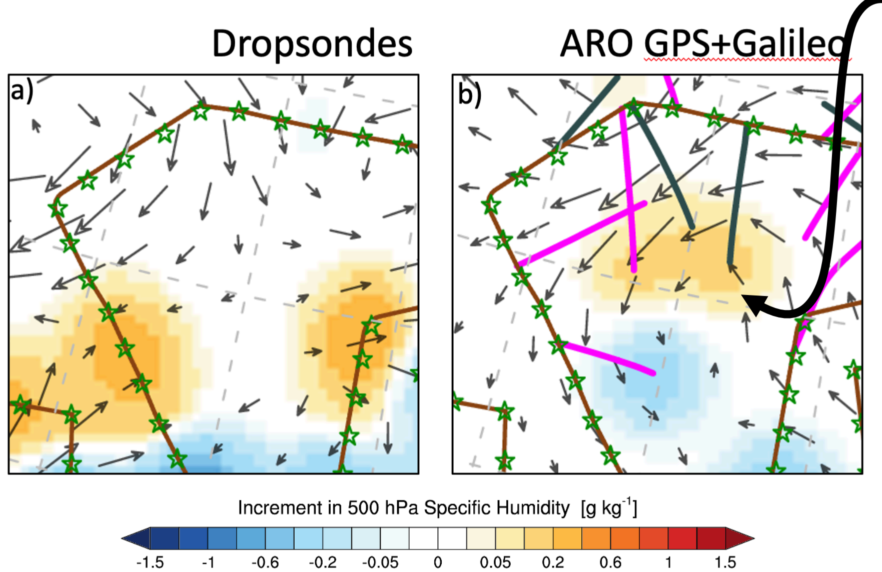


ARO retrieves a profile of refractivity values at the midpoints of the raypaths each time a GNSS satellite sets.

The refractivity

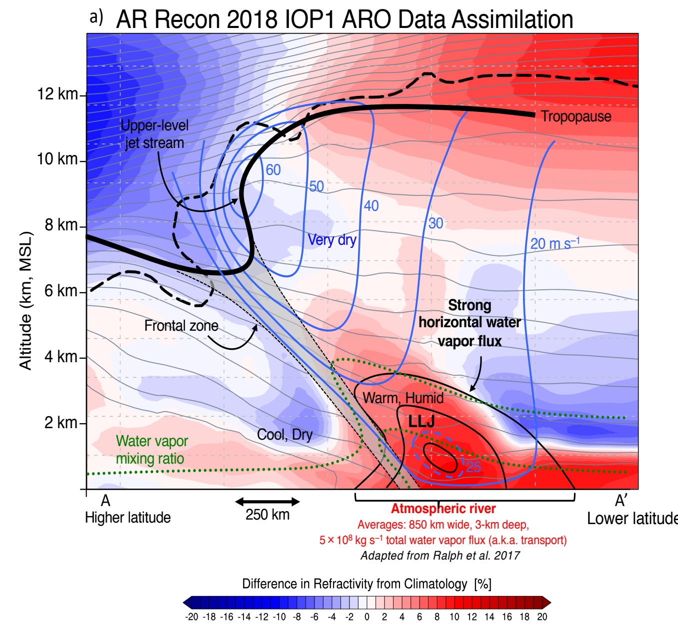
$N \sim k_1\, p/T + k_2\, e/T^2$

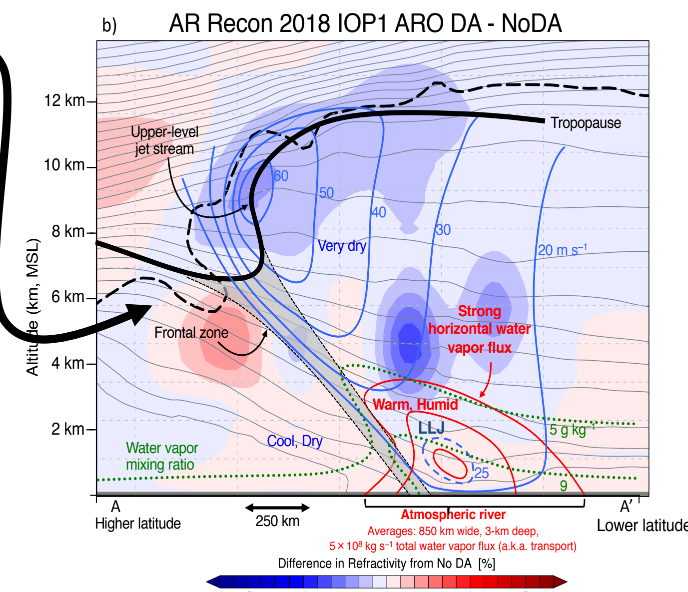
which is the native variable sensed by ARO, reveals distinguishing characteristics of the dynamic tropopause, AR low-level jet, and boundary layer.



ARO modifies the moisture field in areas not sampled by the dropsondes.

The challenge is to observe deeper into the boundary layer with a GNSS signal recorder and open-loop tracking.





ARO deployment during AR Recon - leveraging support from NASA, NOAA, NSF, ONR

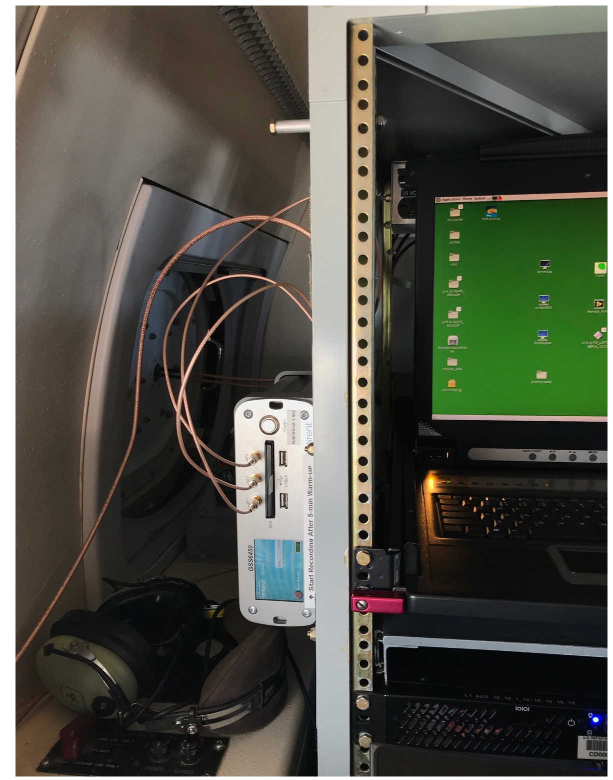
NSF/NASA Dual-pol side-looking antenna

NSF ROC2 occultation receiver

Septentrio Asterxu phase tracking receiver

NOAA Grav-D real-time GNSS/IMU positioning system

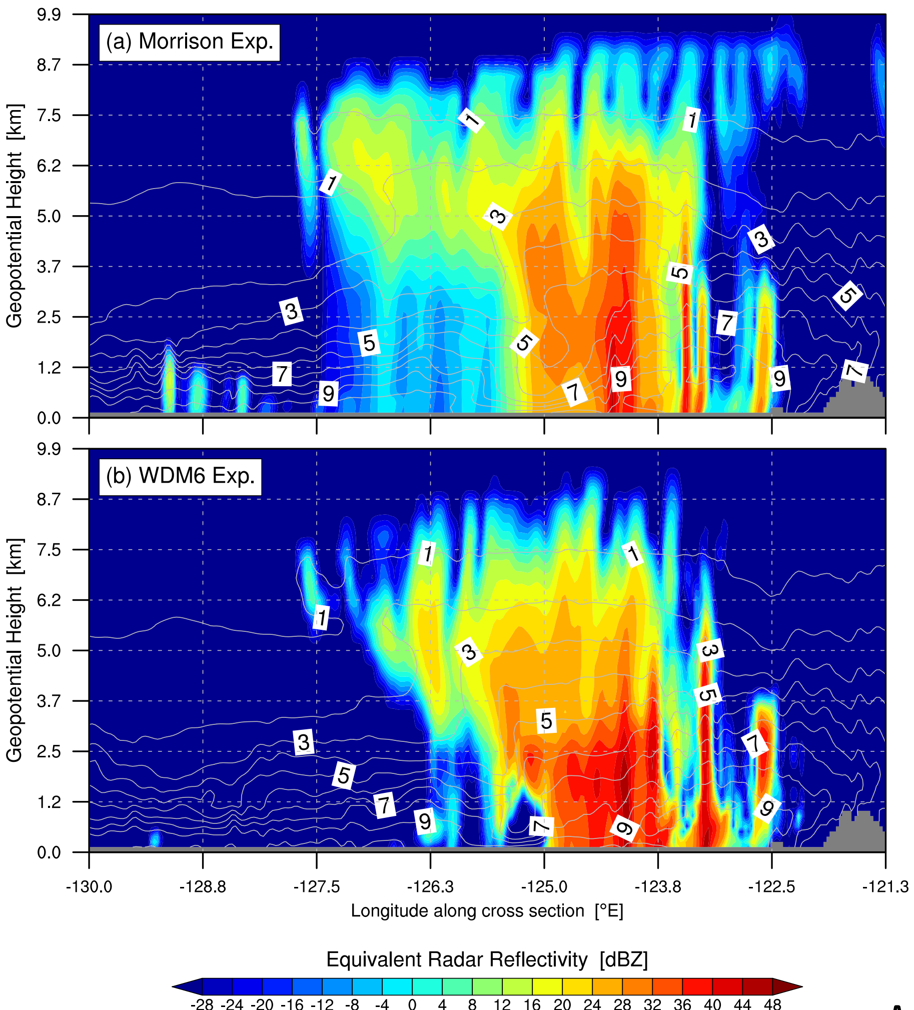
New NOAA multi-GNSS L-band antenna



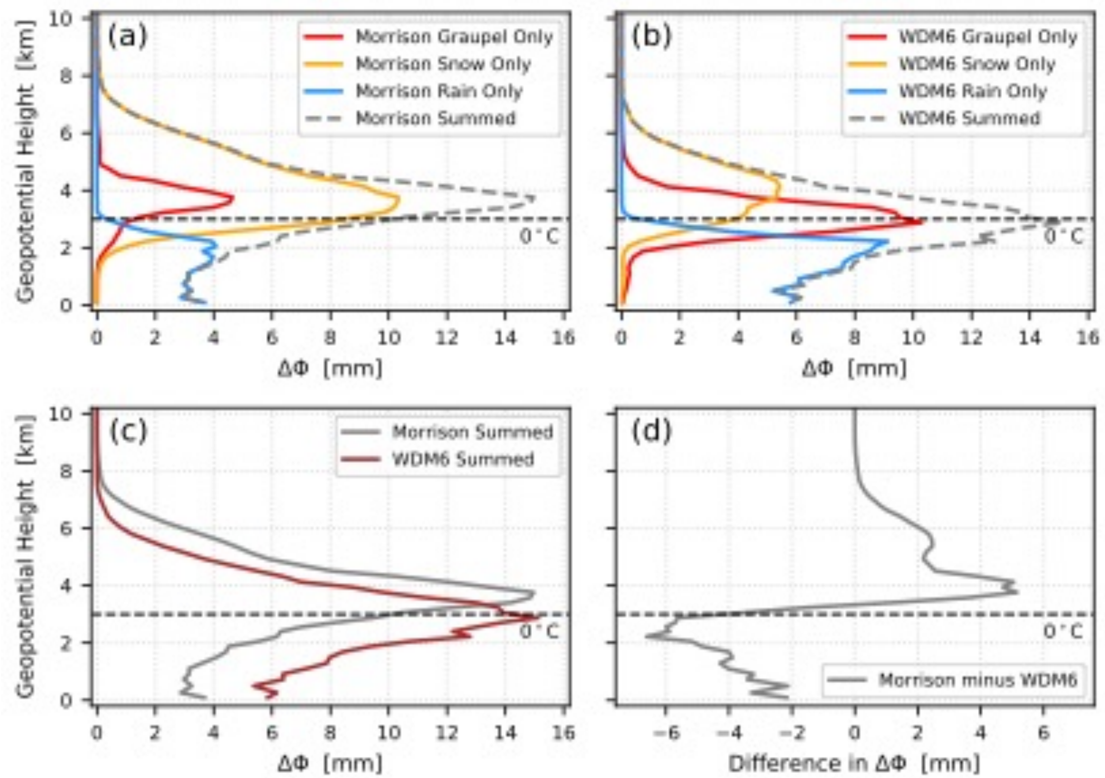
ONR Spirent GNSS signal recorder for development of lower troposphere occultations

CW3E

H-V polarimetric observations of hydrometeors

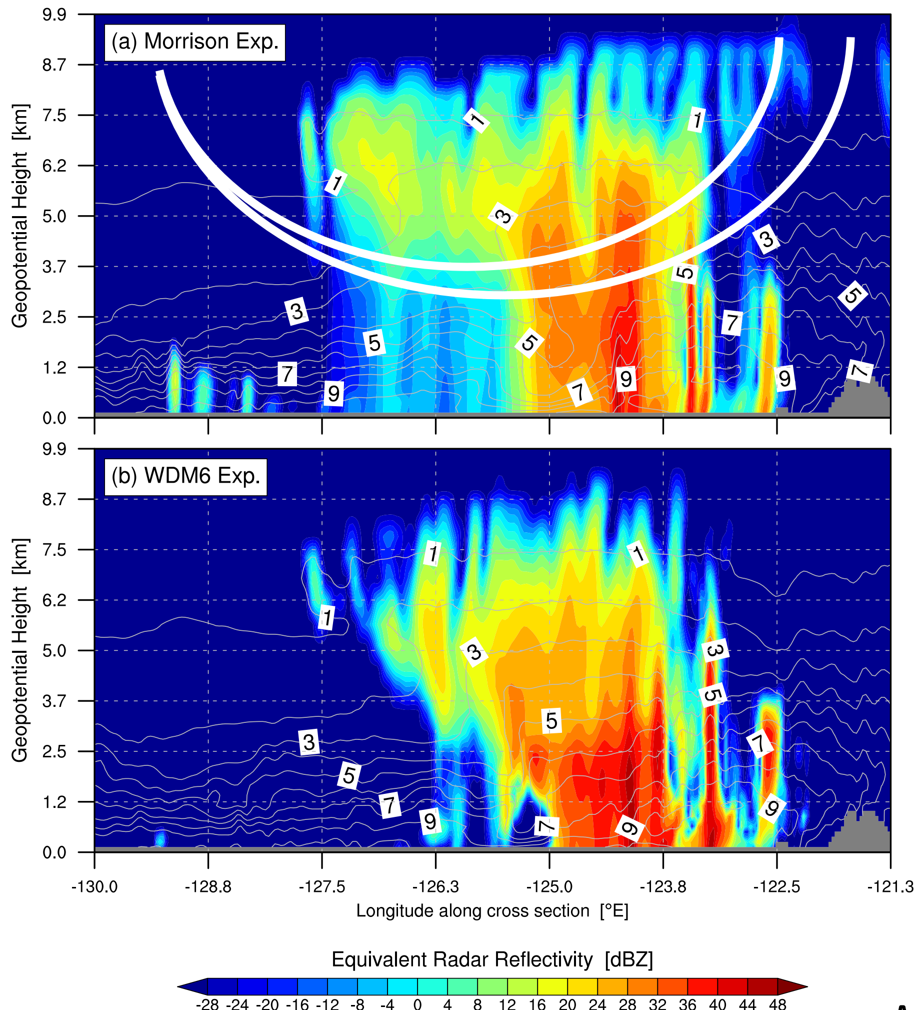


Simulations show the performance of different microphysical parameterizations can be distinguished from polarimetric observations. Largest signal is at ice/rain transition.



Murphy et al., The potential for discriminating microphysical processes in numerical weather forecasts using airborne polarimetric radio occultations, Remote Sensing, *2019*

H-V polarimetric observations of hydrometeors



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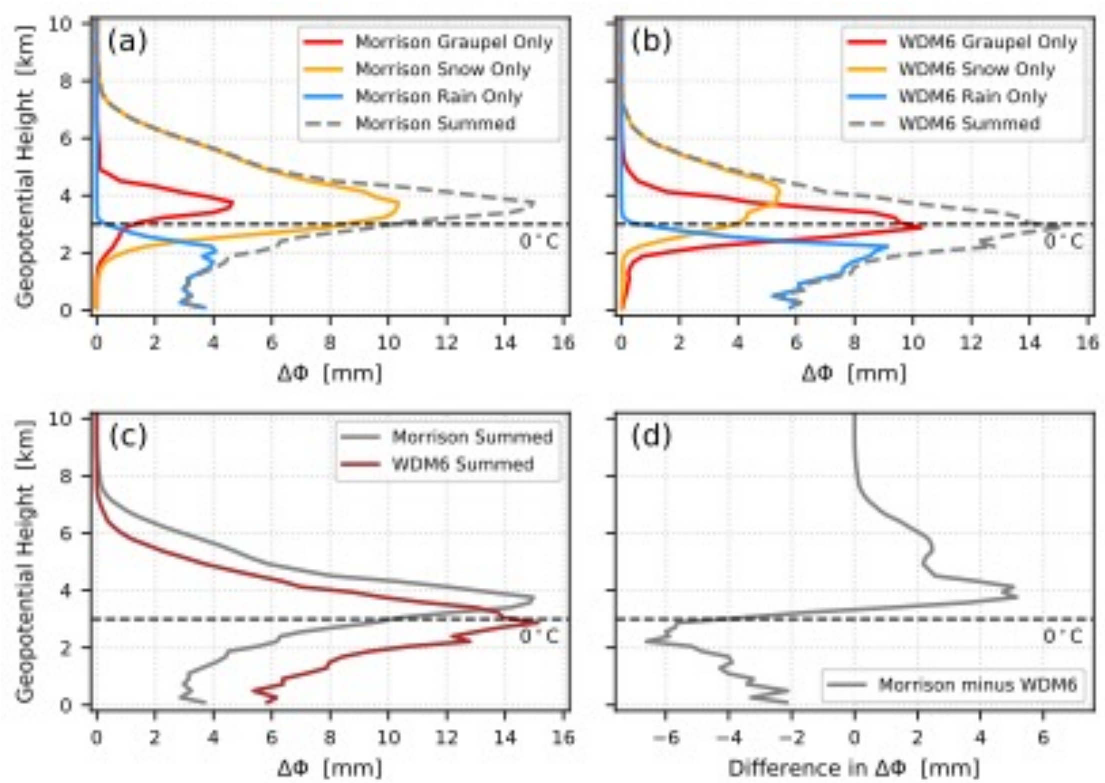
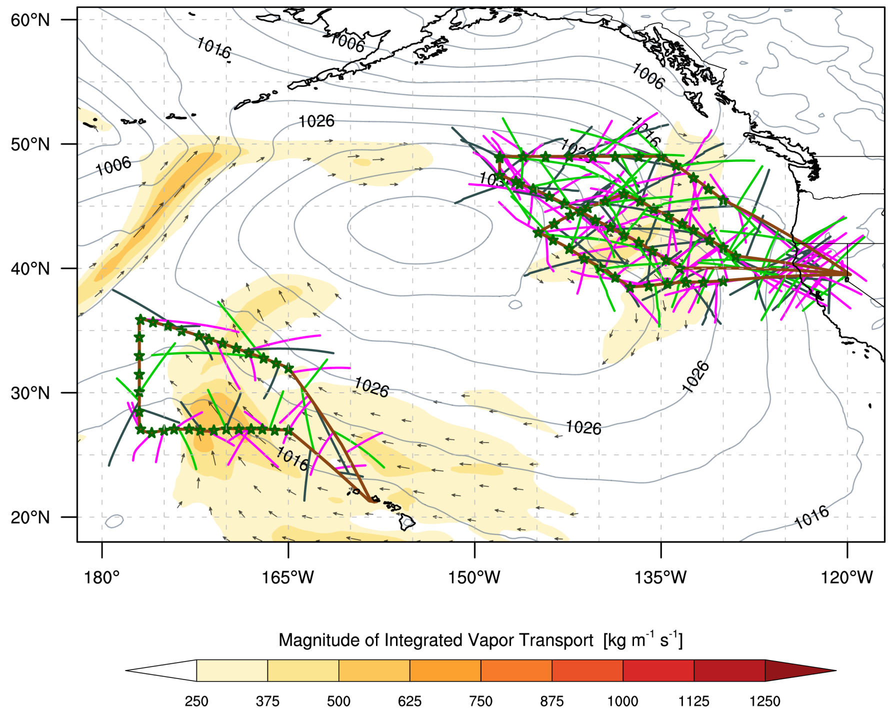
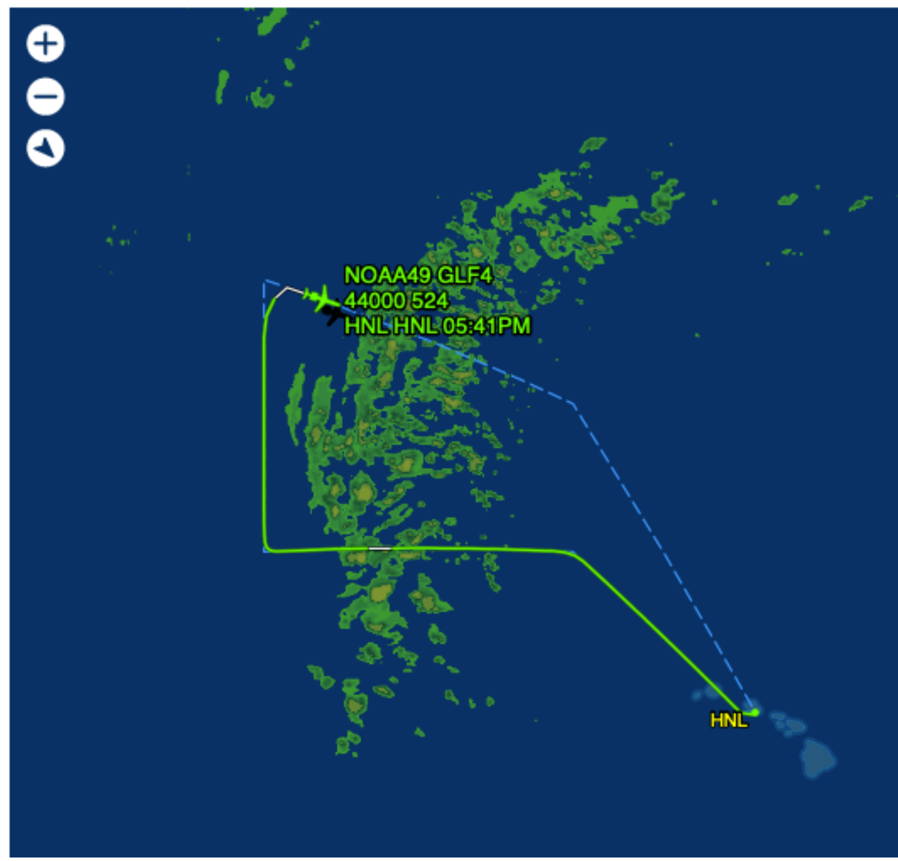


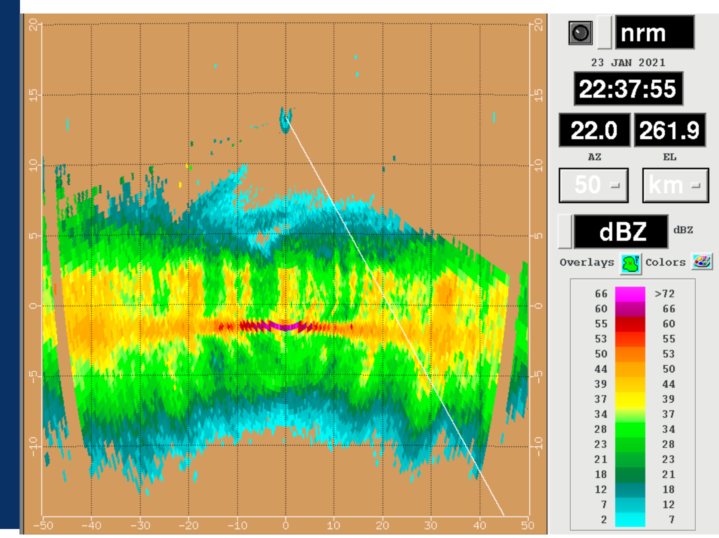
Murphy et al., The potential for discriminating microphysical processes in numerical weather forecasts using airborne polarimetric radio occultations, Remote Sensing, *2019*

H-V polarimetric observations of hydrometeors

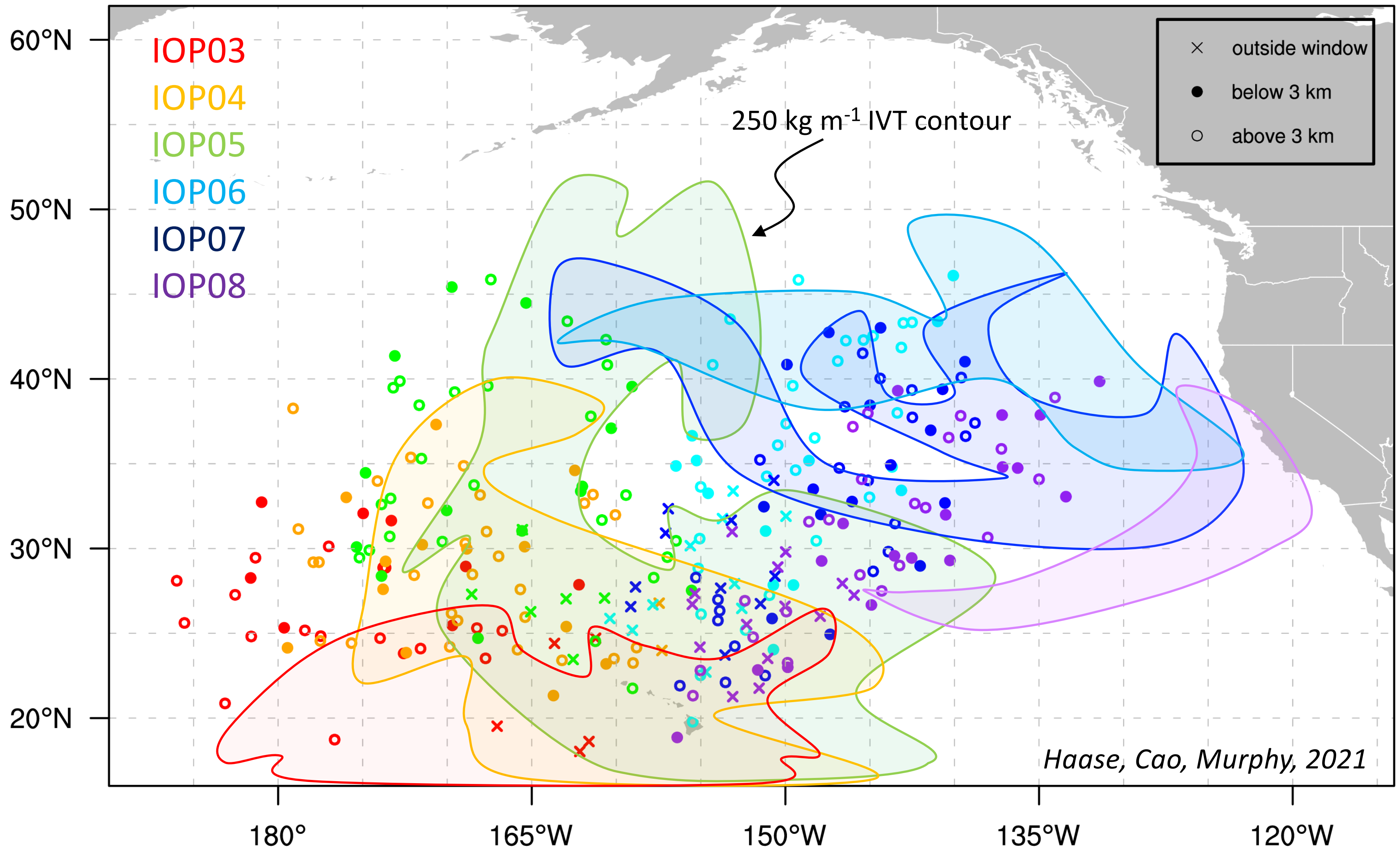
- 3 Channel Spirent recorded top antenna and H/V signals from a side antenna
- Several good events with moderate convective activity
- G-IV Tail Doppler Radar observed the same events



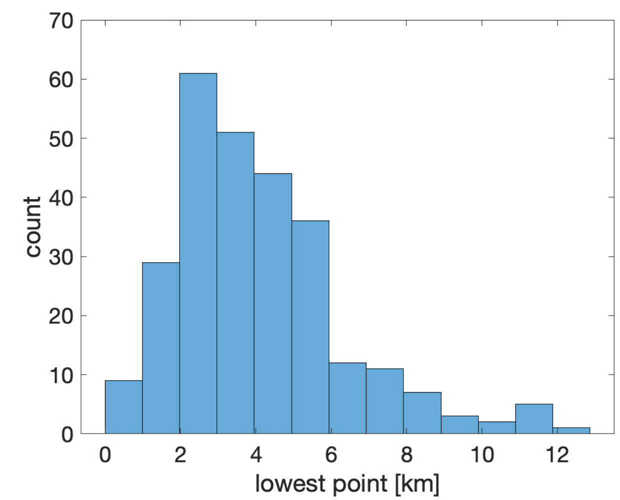




Lowest Airborne RO Tangent points for each Occultation collected during AR Recon 2021 Seq 01 from NOAA G-IV



ARO observes continuously during flight and samples areas inside and outside the areas of highest sensitivity.
ARO profiles extend from flight level to a median height of 3.6 km.
271 total profiles were retrieved from IOP03-IOP08.
224 were within the 6 hr DA window.
101 profiles ended below 3km.



ARO data collected AR Recon 2021

GIV flight	Predicted Occ	Total Occ	Occ inside 0Z window	Occ below 3 km	Real-time Nav PP7 (MB)	Mid-upper trop AsteRx-U (MB)	Side-looking ROC2 (MB)	Lower trop Spirent (GB)	USAF C-130 ROC2.7	USAF C-130 ROC2.8
22	1309	857	259	128	1473	2882	452	16502	8	13
		estimated								

8 flights processed so far

L1 data only –
future research area

Estimate based on
68% retrieval rate

Summary

- Flights over northeast Pacific atmospheric rivers provide dense airborne radio occultation and dropsonde data for assimilation in models.
- The first Galileo RO profiles are compared with nearby Global Positioning System (GPS) profiles to assess accuracy in the troposphere.
- Assimilation of ARO data usefully extends the impact into otherwise unobserved areas.
- The model refractivity anomaly distinguishes key characteristics of the atmospheric river including the low-level jet and tropopause fold.

Summary

- AR2021 Summary
  - AR Recon field campaign in 2018, 2019, 2020, 2021
  - Increasing number of flights 6, 3, 17, 22
  - Advances: multi-GNSS antenna, real-time GNSS/IMU precise positioning, GNSS recorder for open loop tracking, and H/V polarimetric measurements of hydrometeors
  - Consistently retrieving ~45 profiles per flight with ~1/3 extending below 3 km.
- Future scientific investigations:
  - Data impact in areas of sensitivity
  - Analysis of open-loop lower troposphere and H/V Pol observations
  - Resolving areas of latent heat release and convection in core of AR